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GROUND-BASED SENSORS FOR THE
SR-71 SONIC BOOM PROPAGATION EXPERIMENT

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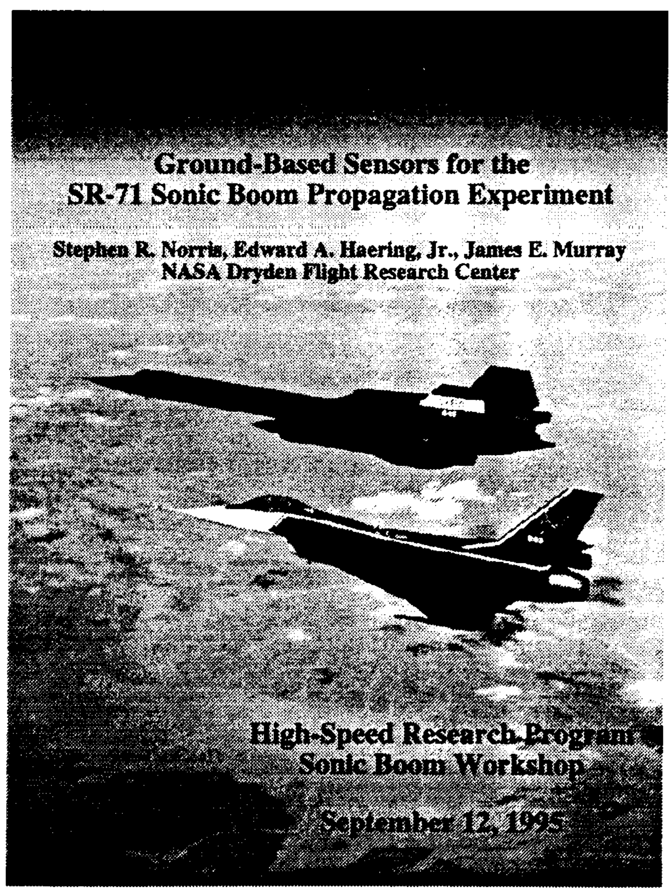
ABSTRACT

This paper describes ground-level measurements of sonic boom signatures made as part of the SR-71 sonic boom propagation experiment recently completed at NASA Dryden Flight Research Center, Edwards, California. Ground-level measurements were the final stage of this experiment which also included airborne measurements at near and intermediate distances from an SR-71 research aircraft. Three types of sensors were deployed to three station locations near the aircraft ground track. Pressure data were collected for flight conditions from Mach 1.25 to Mach 1.60 at altitudes from 30,000 to 48,000 ft. Ground-level measurement techniques, comparisons of data sets from different ground sensors, and sensor system strengths and weaknesses are discussed. The well-known N-wave structure dominated the sonic boom signatures generated by the SR-71 aircraft at most of these conditions. Variations in boom shape caused by atmospheric turbulence, focusing effects, or both, were observed for several flights. Peak pressure and boom event duration showed some dependence on aircraft gross weight. The sonic boom signatures collected in this experiment are being compiled in a data base for distribution in support of the High Speed Research Program.



The behavior of shock wave systems propagating away from an aircraft is of interest to the High Speed Research program. A key objective is understanding the factors that determine the magnitude of the pressure rise across a shock, rate at which smaller shocks coalesce into larger shock fronts, pressure rise time, and overall boom shape. An experiment to investigate these characteristics was completed at NASA Dryden Flight Research Center, Edwards, California, in May 1995. The flight data will be made available to industry and academia for use in development and validation of sonic boom prediction methods.

In this study, an SR-71 research aircraft (Lockheed Corp., Burbank, California) was used to generate a shock wave system while flying at speeds from Mach 1.25 to Mach 1.60 and altitudes from 30,000 to 48,000 ft. The near-field shock system was probed by an F-16XL research aircraft (General Dynamics, Ft. Worth, Texas) at a vertical displacement from the SR-71 aircraft of distances up to 8000 ft. Low altitude measurements were taken by a Y0-3A aircraft (Lockheed Corp., Burbank, California) flying at approximately 10,000 ft and carrying microphones at its wingtips and tail (Haering, Ehernberger, and Whitmore, 1995). A third set of measurements was collected at ground level. Ground instrumentation consisted of Portable Automatic Triggering Systems (PATS), the prototype of a new sonic boom recorder called the Small Airborne Boom Event Recorder (SABER), and two digital MiniDisc recorders (Sony Corporation, Tokyo, Japan). See slide 1. This study extensively used the Global Positioning System (GPS) satellite navigation network to determine the relative positions of the shock-generating aircraft, probe aircraft, and ground-level recording equipment.

Introduction

- **A sonic boom flight experiment by the High Speed Research team was recently completed at NASA Dryden Flight Research Center**

- **Data sources**
  - **- Shock generator: SR-71**
  - **- Near-field probing aircraft: F-16XL**
  - **- Far-field monitoring aircraft: Y0-3A**
  - **- Weather balloons**
  - **- Ground sensors**

- **Ground measurement equipment**
  - **- Portable Automatic Triggering Systems (PATS)**
  - **- Small Airborne Boom Event Recorder (SABER)**
  - **- MiniDisc recorders**

Slide 1

This presentation focuses on measurements made at ground level (slide 2). Several sonic boom measurement systems, sensor layout, SR-71 flight conditions, and sample data sets will be discussed. These results are preliminary, but the full data sets will be published for future distribution.

Outline

- Sensor systems used at ground level
- Introduction of sensor system under development
- Matrix of flight test conditions
- Position and distribution of ground sensors
- Sample results and discussion
- Summary

Slide 2

The PATS units were used as the primary instrumentation at the ground stations. Each PATS is the size of a large briefcase (slide 3). The electronics are nested in a foam pad which is enclosed in a hard plastic case.

The transducer is at the end of a cable, so it can be moved several feet away from the main box. The reference side of this differential pressure transducer is evacuated to approximately one-half atmosphere and sealed. The transducer output is conditioned by a high-pass filter with a cutoff frequency of approximately 0.3 Hz.

Each PATS can record eight time histories of pressure data. At least one of these time histories must be a calibration signal from an acoustical calibrator, but typically more than one calibration signal was recorded on each unit.

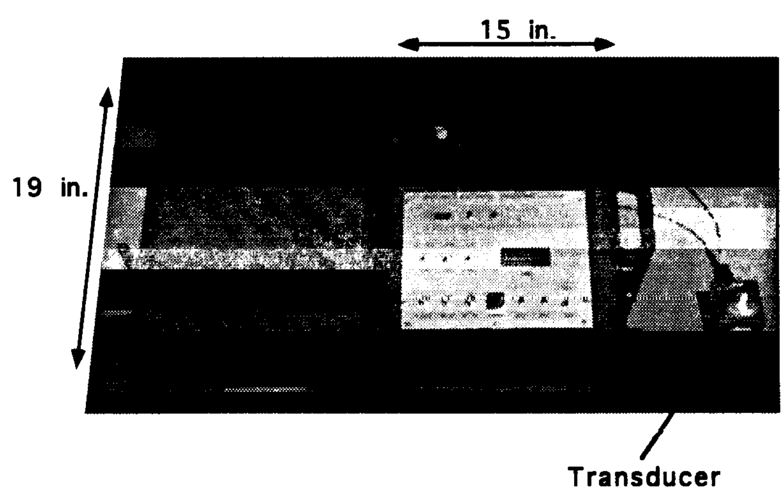
The acoustical calibrator is a device that puts out a tone of known frequency and loudness (dB level). Postflight processing of calibration files is used to determine the relationship between digital counts recorded by the PATS and pressure levels from the recorded sonic boom data. This procedure is necessary because of changes in calibration parameters caused by shifts in ambient temperature and pressure.

Noise sources in the test environment, such as wind or the presence of other high speed aircraft, had the potential to cause false triggering of the units. Because of the small amount of memory in each PATS unit, it was necessary to monitor the PATS during testing to avoid using memory for extraneous data.

Two types of PATS were used. The 8-bit model had 8 bits of resolution, while the "16-bit" model had 15 bits of resolution. The additional resolution of the 16-bit units was not necessarily an advantage.

Transducer gain and trigger levels were adjusted to match the flight conditions. These adjustments were not perfected on the 16-bit units until after flight 23. Details about the PATS have been published previously (Stansbery and Stanley, 1989).

Portable Automatic Triggering System (PATS)



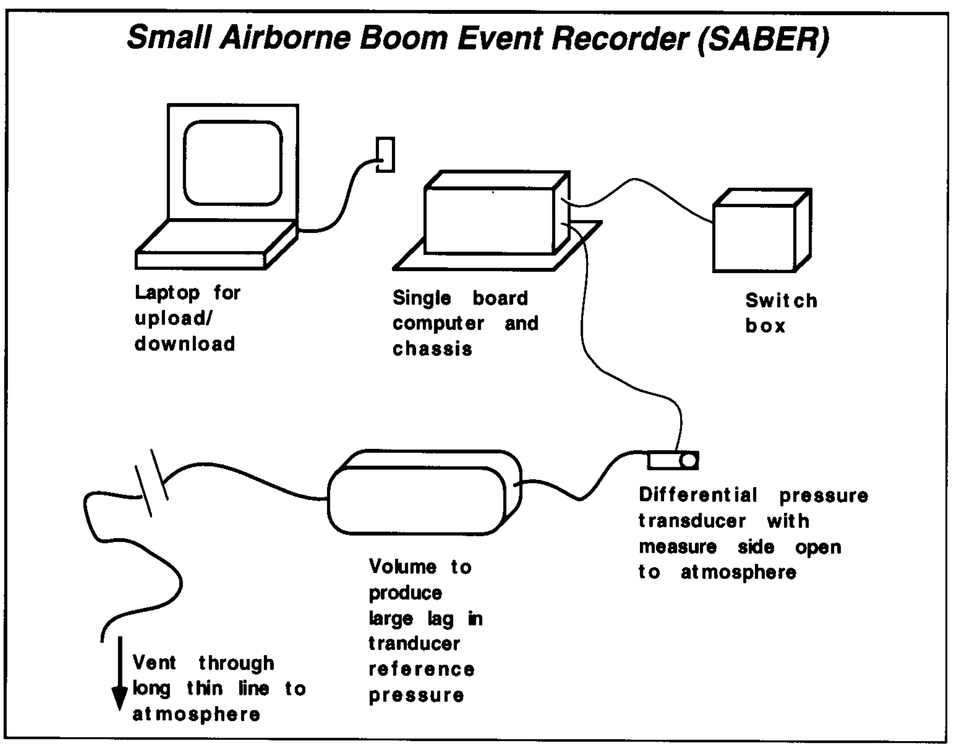
Slide 3

Slide 4 shows the schematic of a prototype device referred to as the SABER. Based on a commercially available single board computer, this device was used to record several ground signatures during the flight program. Such computers have been used in a variety of flight applications (Hamory and Murray, 1994). The SABER was designed as flight hardware, but successful in-flight use has not been demonstrated.

Operation of the SABER is the same as that of the PATS. The SABER "listens" for the rapid pressure rise associated with a sonic boom. It then records and holds that data until the user can download the buffer contents. Interface with the unit is accomplished with a laptop computer. Each signature is tagged with an appropriate time so that a data set can be correlated with the triggering event.

The SABER has a large amount of onboard random access memory (RAM), allowing approximately 50 separate pressure time histories of 2 sec length to be recorded at 10,000 samples/sec. By comparison, the older PATS could hold 8 time histories of 2 sec length at 8000 samples/sec.

The SABER uses a differential pressure transducer as the sensing element. The sensor side of the transducer is vented directly to the atmosphere. The reference side of the transducer is plumbed to the atmosphere through a tank and line to form an overdamped low-pass filter with a time constant of several seconds. This blocks high-frequency pressure fluctuations (for example, sonic booms) from the transducer reference side while passing low frequency pressure fluctuations (for example, slow atmospheric variations). A low-pass antialiasing filter is also used, so the system acts as a band-pass filter.



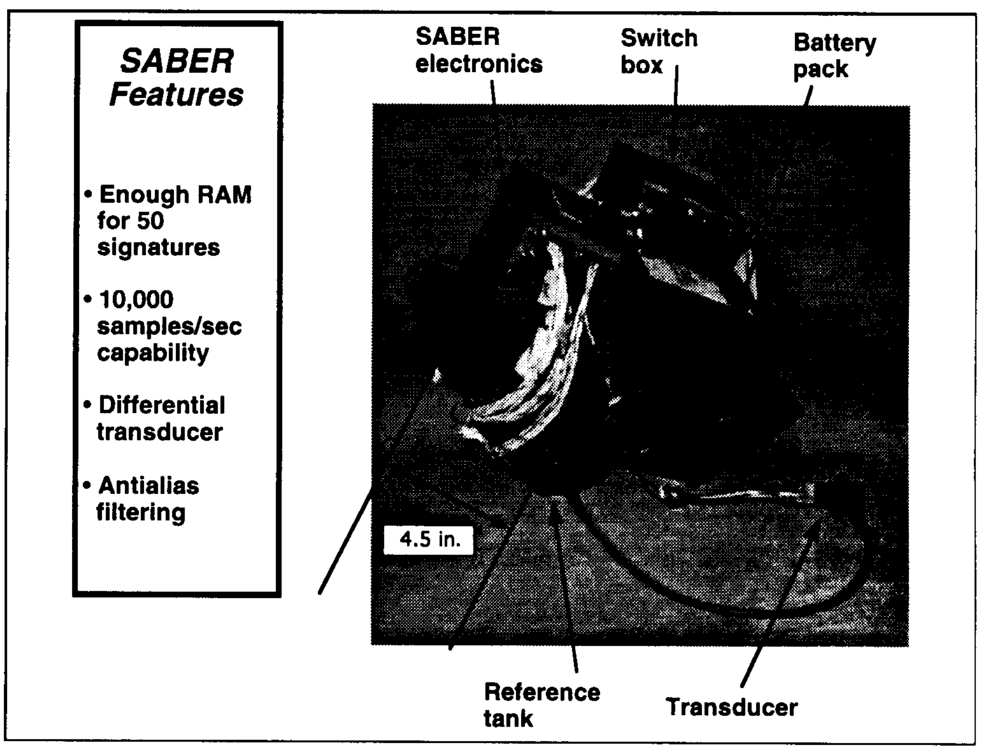
Slide 4

This configuration has two advantages over an absolute-pressure-based sensing system, such as the one used by the PATS. In a quiet atmosphere, the differential pressure is zero, allowing an extremely sensitive (± 21 psf) transducer to be used. Amplifier gain is reduced, thus signal-to-noise ratio is increased. Additionally, insensitivity of the system to slow atmospheric pressure changes allows it to be used on an aircraft at varying altitudes.

The SABER was designed to rely on an in-house calibration of its pressure transducer. While only one set of calibration parameters was used for these tests, the potential exists for the SABER to record transducer temperatures so that appropriate adjustments can be made to compensate for temperature fluctuations. This would be particularly important for large temperature ranges often encountered in flight.

The system allows quick adjustment of signal gain and antialias filter cutoff frequency through the use of its signal processing card. Trigger criteria may be changed at the software level.

Slide 5 shows a picture of the prototype SABER. Development of the package is still underway concerning choices of filter frequencies, optimum reference tank configuration, and triggering criteria.

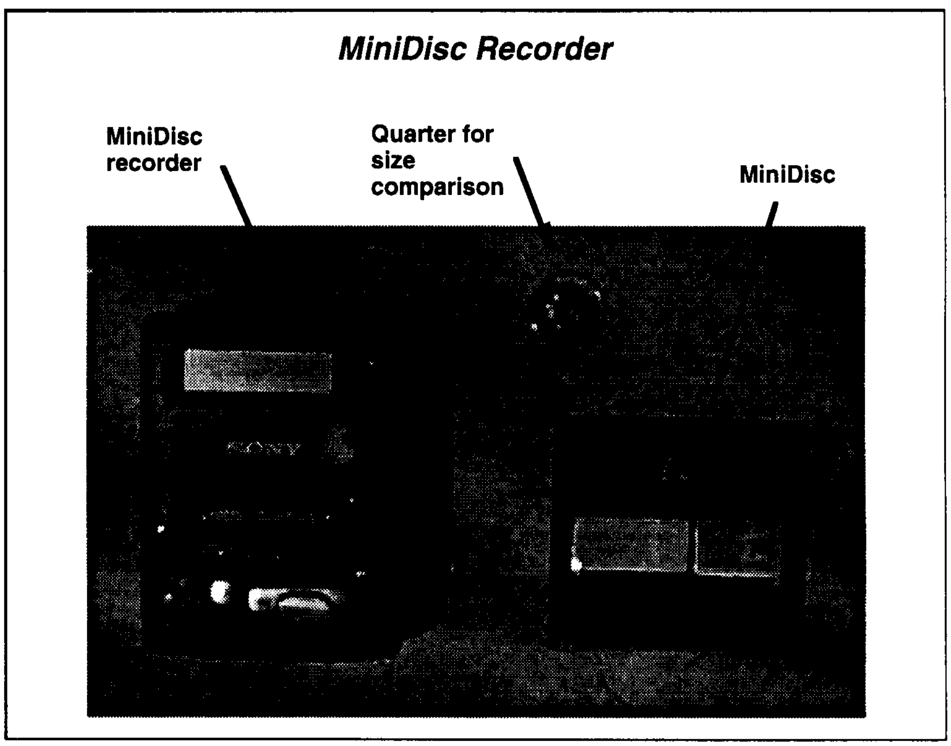


Slide 5

Audio recordings were obtained for most of the sonic boom flights using two MiniDisc recorders (slide 6). A quarter is shown in the picture to demonstrate system size. The recorder writes to an optical magnetic disc that stores the information digitally. Each MiniDisc holds up to 74 min of audio recording on up to 255 tracks.

The recordings made later in the project are better than earlier efforts. Trial-and-error attempts showed the necessity of using manually controlled record levels set near the lowest level. Two instrumentation microphones were used with each of the two MiniDisc recorders. One was placed at ground level, and the other was elevated on a tripod.

A calibration signal was recorded for each microphone for every test flight to allow future conversion of the audio recordings to pressure levels. The microphones do not have the low-frequency capability of a pressure transducer, but the high-frequency data may be used to complement the transducer data. Listening to these recordings gives a qualitative measure of the loudness of a boom as well as some measure of ambient noise levels caused by wind and other aircraft.



Slide 6

A time history of the pressure level during a sonic boom event contains very high and very low frequency components. Every sensor has its own frequency response. As a result, a recorded sonic boom signature consists of an actual physical boom event in combination with some distortion because of transducer or microphone dynamics. Slide 7 shows a comparison of the dynamic response of the different sonic boom sensors.

The PATS transducer has a sealed reference side. The transducer signal is conditioned by a high-pass filter with a cutoff frequency of approximately 0.3 Hz. The full-scale pressure range for each unit varies, with values of 11 to 16 psf for the 16-bit units. The 8-bit PATS have full-scale values of 6 to 15 psf. The 8-bit units have 2^8 levels of resolution, while the 16-bit units have 2^{15} levels of resolution.

The SABER uses a full-bridge differential pressure transducer with a full-scale range of 42 psf with 2^{12} levels of resolution. The transducer used in the prototype has a frequency response upper limit of approximately 2000 Hz, but the overall system response is forced lower by the antialiasing filter. The antialiasing cutoff frequency may be raised for future tests.

The MiniDisc recorders were connected to two capacitive microphones to record sound levels. The system is designed to capture frequencies of 20 to 20,000 Hz.

Sensor System Specifications

Sensor type	Sensor frequency response, Hz	System band-width, Hz	Sample rate, Hz	Approx. res., psf/bit	Approx. noise level, psf
16-bit PATS	0.3 - 10,000	0.3 - 4,000	8,000	0.0004	0.3
8-bit PATS	0.3 - 10,000	0.3 - 4,000	8,000	0.0420	0.2
SABER	0.1 - 2,000	0.1 - 1,020	10,000 *	0.0153	0.06
MiniDisc	20 - 20,000	20-20,000	44,100 *	- - -	- - -

*** Includes an antialiasing filter.**

Slide 7

Eight research flights with 19 test points were conducted between February 15, 1995, and April 20, 1995. Slide 8 presents the nominal test conditions and number of ground signatures recorded for each test flight. The rows enclosed by the dark box correspond to flight conditions of high-altitude and low supersonic Mach number, resulting in ground signatures that were so weak that little or no data were captured. An asterisk (*) in the SABER column indicates that the SABER prototype was not deployed for the corresponding flight.

Actual flight conditions are not perfectly steady, so more precise determination of aircraft flight conditions may be obtained by iterative forward throw calculations. Forward throw is the distance from the point where a shock wave is generated (at the aircraft) to the spot where the propagating shock wave intercepts a point of interest (the ground station). Iterative calculations of forward throw for a selected segment of an SR-71 flight should reveal the actual flight conditions that correspond to a given boom event recorded on the ground. These step-wise calculations require weather data that will also be supplied in the data base.

SR-71 Flight Test Matrix

Flight	Pass	Mach number	Altitude, ft	Gross weight, lb	8-bit PATS data sets	16-bit PATS data sets	SABER data set	MiniDisc data sets
23	1	1.25	30 K	110,000	2	3	No	2
	2	1.25	30 K	85,000	2	2	Yes	
24	1	1.25	30 K	110,000	4	6	Yes	2
	2	1.25	30 K	100,000	4	4	Yes	
	3	1.25	30 K	80,000	3	4	Yes	
25	1	1.25	30 K	120,000	3	7	No	5
	2	1.25	30 K	100,000	2	9	No	
	3	1.25	30 K	80,000	2	9	Yes	
26	1	1.50	48 K	95,000	4	8	No	3
	2	1.50	38 K	85,000	4	8	No	
27	1	1.50	48 K	110,000	4	6	No*	4
	2	1.50	48 K	90,000	4	6	No*	
28	1	1.50	48 K	110,000	4	3	Yes	4
	2	1.50	48 K	85,000	4	3	Yes	
29	1	1.25	44 K	110,000	0	0	No	4
	2	1.25	44 K	85,000	0	0	Yes	
30	1	1.25	44 K	110,000	0	0	No	3
	2	1.25	44 K	90,000	1	2	No	
	3	1.25	30 K	75,000	3	6	Yes	
Totals					50	86	9	27

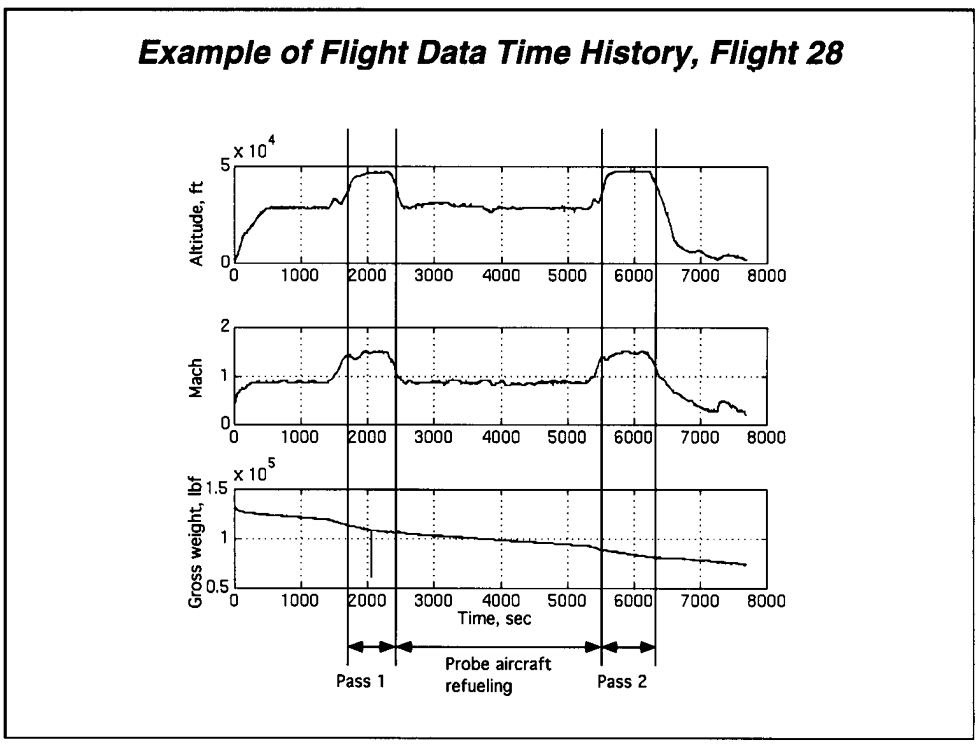
Slide 8

Slide 9 shows a sample time history of altitude, Mach number, and gross weight for flight 28. This time history provides an example of altitude and Mach number variability during a research flight.

At supersonic speeds, the SR-71 aircraft generated numerous shock waves that emanated from major components, such as the bow, canopy, inlets, wings, and vertical tails. The F-16XL probe aircraft was flown behind and below the SR-71 at predetermined vertical separations of up to 8000 ft to measure the changes in pressure across the individual shocks. These measurements characterized the component shocks as well as the rate at which these shocks coalesced into two shock fronts.

The SR-71 and the F-16XL aircraft flew at nearly the same speed while the F-16XL aircraft probed in and out of the shock system. Both aircraft generated shock systems that usually propagated to ground level. The two shock systems rarely interfered with each other, so the ground-based sensors often recorded separate boom signatures from both aircraft.

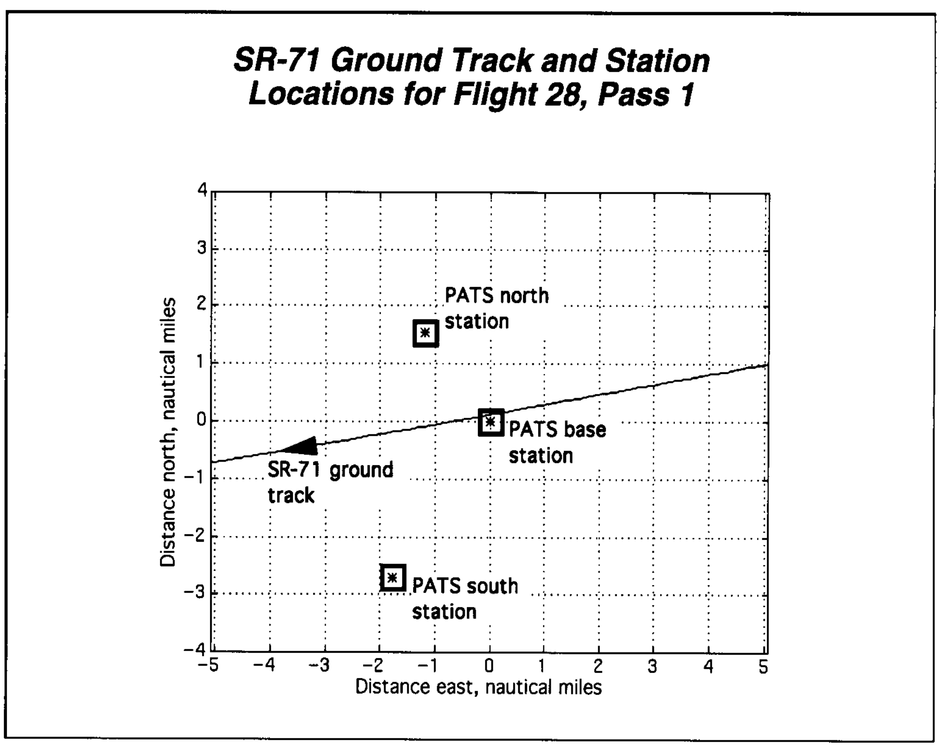
The long supersonic endurance capability of the SR-71 aircraft required the F-16XL aircraft to refuel between test periods. Refueling took place while the SR-71 aircraft flew at subsonic speeds during the period noted in slide 9.



Slide 9

Ground recording equipment was separated into three stations. Station locations were determined with a differential GPS before the flight. The GPS data collected during test flights allow calculation of distances from the ground stations to the aircraft ground track. Slide 10 shows SR-71 GPS data from flight 28 converted to north and east displacement from the base ground station.

The base station was located as close to the predicted ground track of the SR-71 aircraft as possible. Two more stations were located approximately 2 miles north and south of the ground track, depending on site accessibility. This arrangement was chosen so that the SR-71 ground track would come very close to one of the stations even if there were a slight deviation from the predicted flightpath.

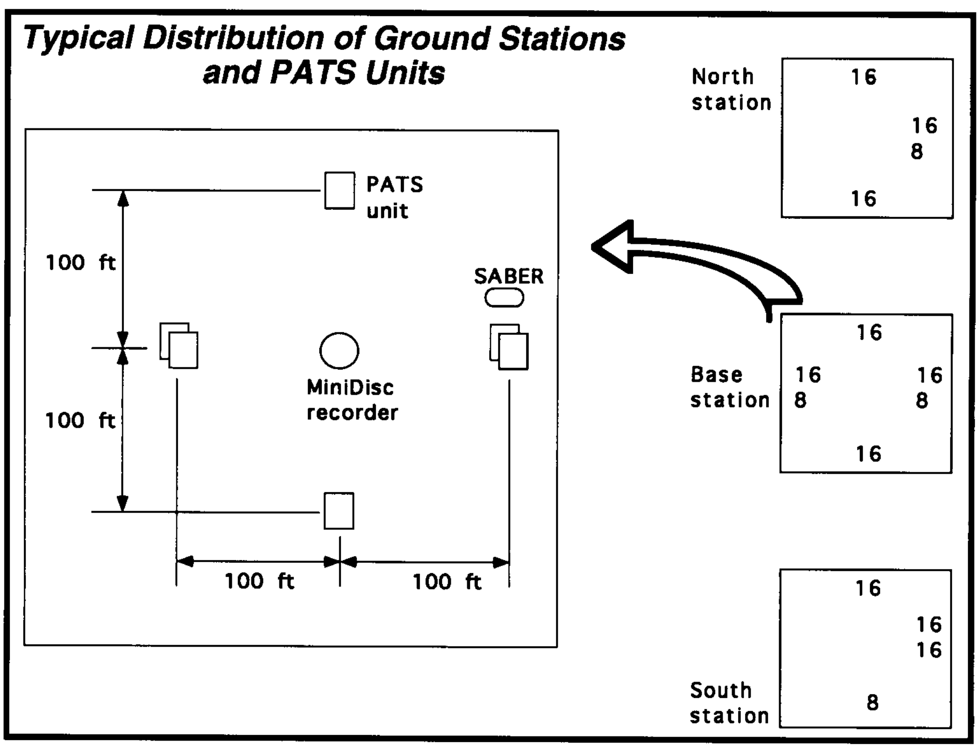


Slide 10

Slide 11 shows a typical distribution of the PATS units. Each ground station included an array of individual pressure sensors, with the PATS units placed approximately 100 ft from a central point. Four of the 8-bit units and 10 of the 16-bit units were used. At least one of the 8-bit PATS was placed at each of the stations. Typically six PATS were placed at the base station, and four were placed at the north and south stations.

Some sensors did not collect data from each pass because of operational problems, such as incorrect trigger levels, operator errors, or unit malfunctions. Documentation will be released with the data sets showing which units captured data successfully on any given flight.

MiniDisc recorders were also used at two of the ground stations to provide audio recordings of the boom events. The SABER prototype was located at the base station next to one of the PATS units.

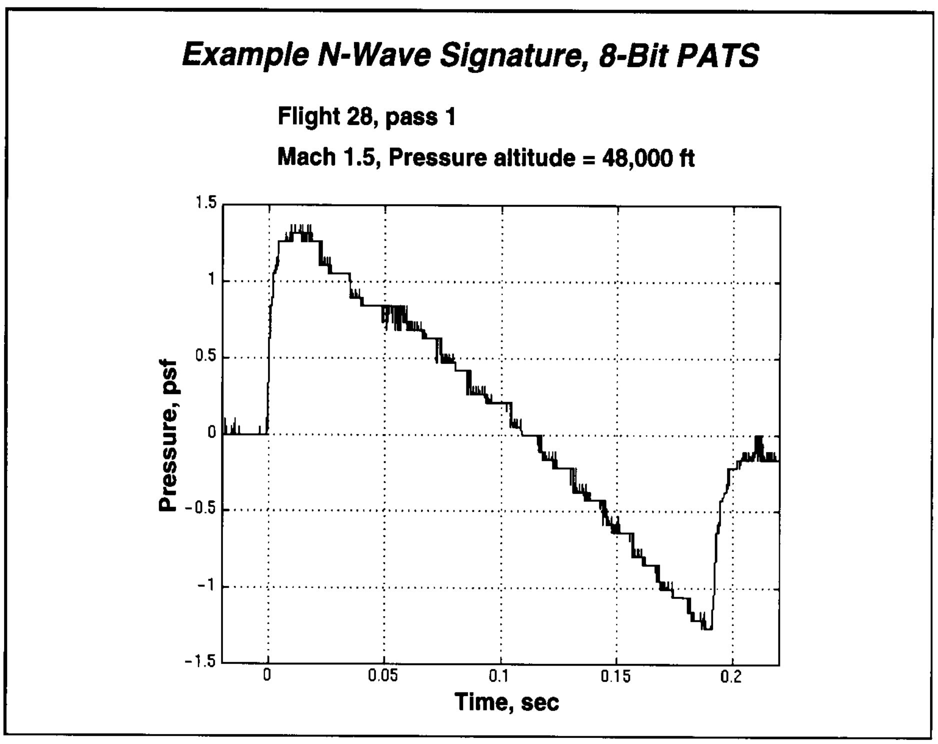


Slide 11

An N-wave boom shape forms when multiple shocks emanating from various parts of a supersonic aircraft coalesce into two large shock fronts. This process results from differences in the speed of sound between the various component shocks. Shocks in the middle of the signature catch up to and merge with the leading shock, resulting in two distinct shock fronts.

Near-field usually refers to regions close to the shock-generating aircraft where the individual component shocks have not yet coalesced. Far-field refers to regions at a great enough distance from the aircraft that the shock system has reached a coalesced condition.

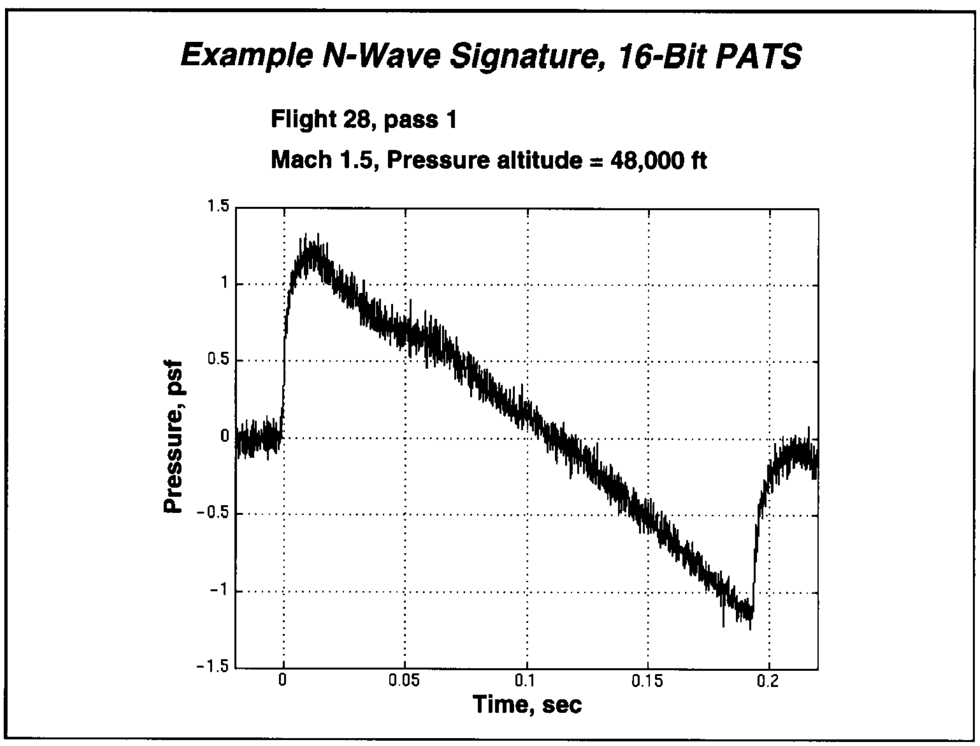
The classic far-field, N-wave boom signature was recorded for many of the flight conditions in this study. Slide 12 shows an example of such a signature from flight 28. These data are from an 8-bit PATS unit with a fairly small noise level; however, the resolution is low, resulting in the stair-step appearance of the data.



Slide 12

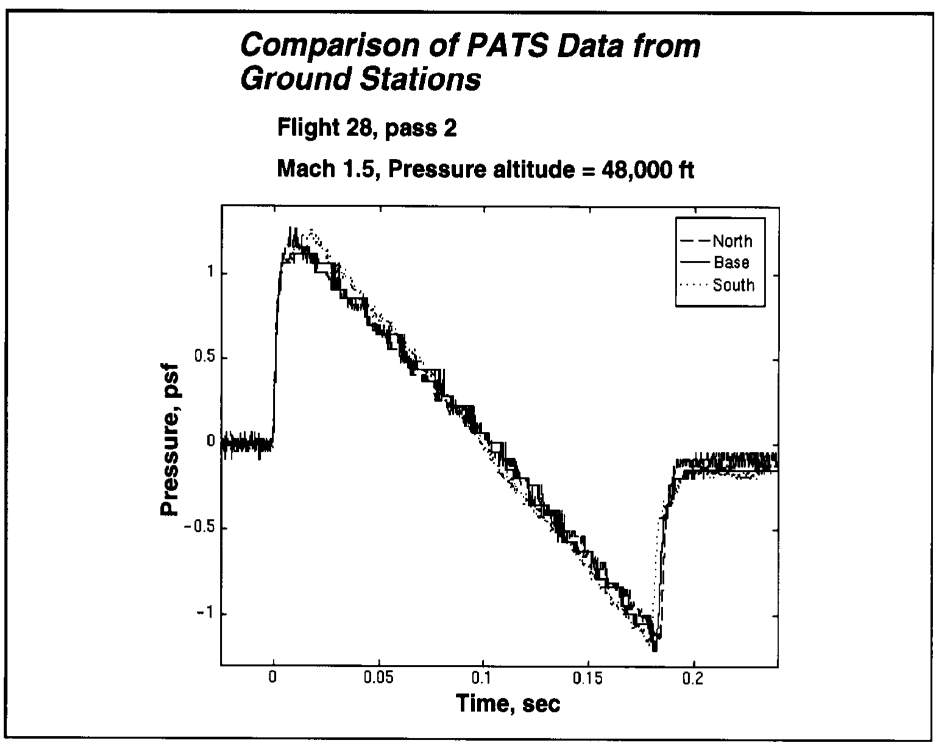
Slide 13 shows a boom signature captured from the same pass as slide 12. This signal came from a 16-bit unit located adjacent to the 8-bit unit that recorded the signature in slide 12.

The additional resolution of the 16-bit units over the older 8-bit units did not prove to be a large improvement because the new units had no corresponding reduction in signal noise levels. The high noise levels may have resulted from large gain values needed for the sealed pressure transducers used in the PATS.



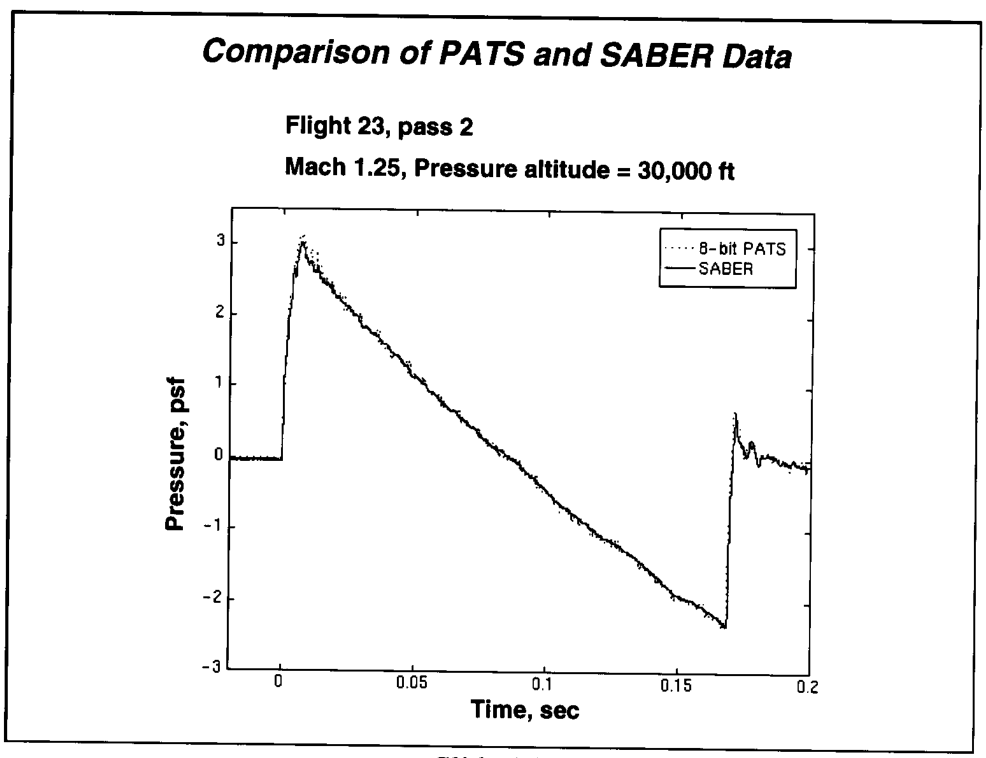
Slide 13

Slide 14 compares sonic boom signatures recorded at the north, base, and south stations for pass 2 of flight 28. These stations were each located close enough to the SR-71 ground track to record similar boom signatures. There is good agreement in the maximum overpressure, boom duration, and wave shape recorded by different PATS units. This agreement was aided by the calm weather conditions present for flight 28.



Slide 14

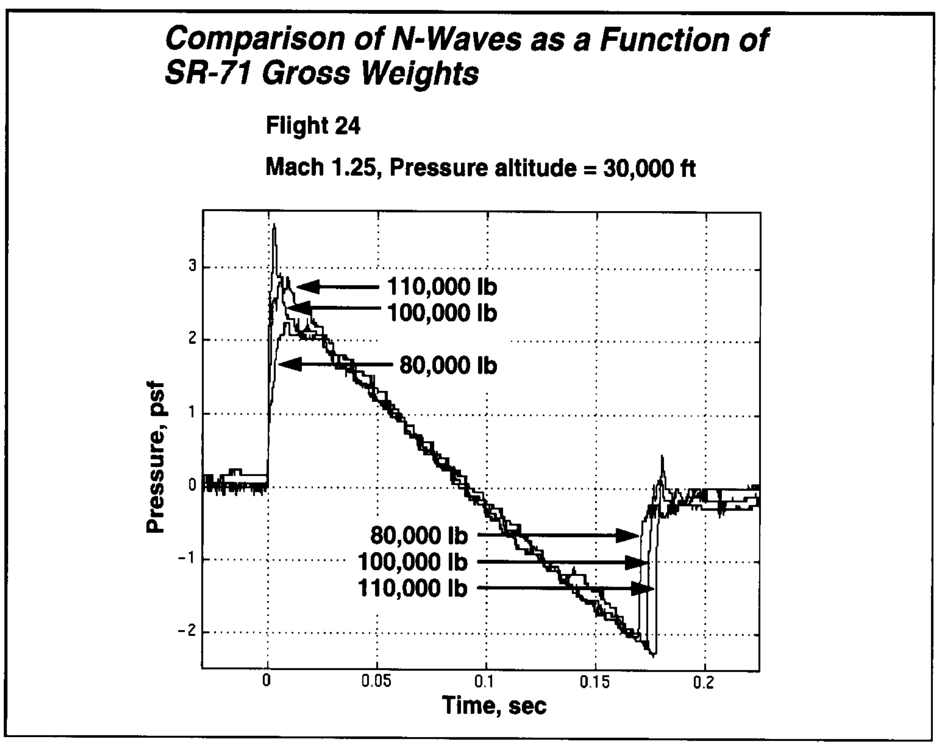
Slide 15 shows a comparison of data sets from the SABER and an 8-bit PATS unit. Excellent agreement is seen in the overpressure, rise time, and other features of the signature. Such comparisons have been used to verify correct operation of the new SABER prototype. The close agreement increased confidence in the results obtained with the PATS units.



Slide 15

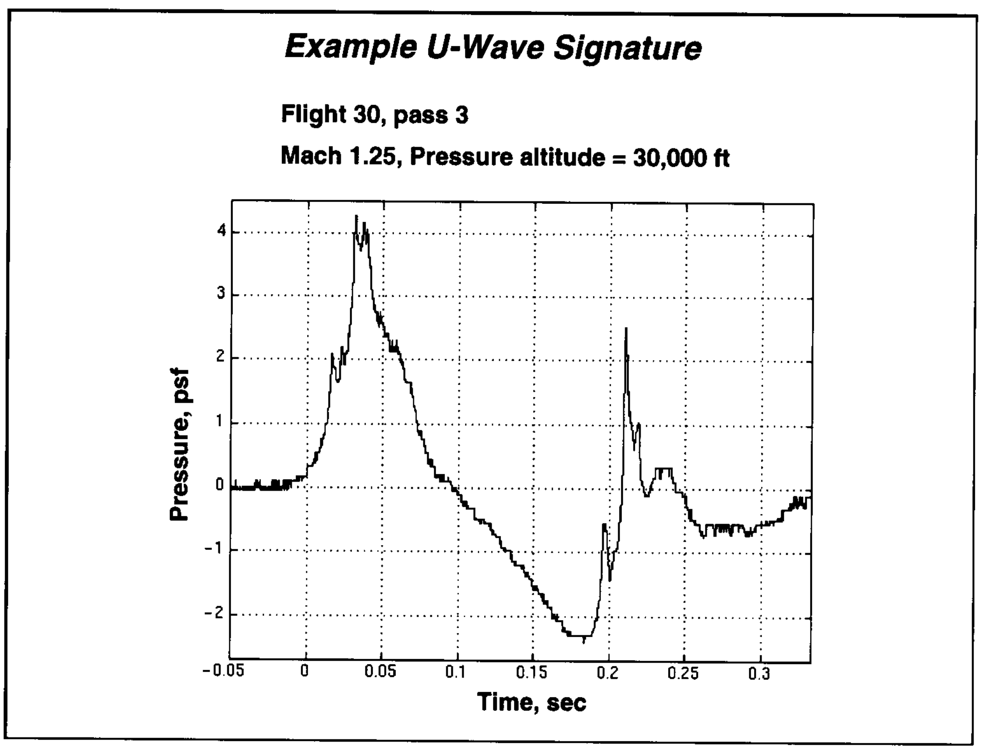
Slide 16 provides an example of the trend in boom signature shape with variations in SR-71 gross weight. These data sets show three passes at consecutively lower gross weights and, therefore, lower lift coefficients. A small peaking effect from the first pass may have somewhat exaggerated the change in maximum overpressure, but the general tendency was reduced maximum overpressure and boom length as the weight decreased with each successive overflight.

Other factors, such as atmospheric turbulence and Mach number, affect boom characteristics. For this reason, gross weight effects could not be isolated in this test. These gross weight effects would, however, be expected because lift magnitude is a significant factor in determining boom characteristics (Darden, et. al., 1989).



Slide 16

Various distortions caused by focusing effects and atmospheric turbulence are known to occur to propagating shock fronts (Lee and Downing, 1991). This focusing can result in a U-shaped boom with relatively high peak overpressures in areas where the foci exist. Several of these types of signatures were captured during flight testing (slide 17).



Slide 17

A total of 172 sonic boom ground signatures were captured during eight sonic boom research flights by an SR-71 aircraft and are being compiled into a data base (slide 18). All three sensor types successfully captured sonic boom ground signatures. Similar results were obtained with both the 8- and 16-bit PATS units. The SABER is a promising device that shows potential as a new sonic boom recording system. Comparisons of pressure time histories recorded by the SABER and the PATS showed excellent agreement. Further development of the SABER is underway. MiniDisc recordings offer a qualitative analysis and expanded high-frequency content for most of the boom events.

Summary of Ground Sensor Equipment

- **172 sonic boom ground signatures captured**
- **Data sets will be made available on electronic media and in NASA publications**
- **8- and 16-bit PATS units showed comparable results for boom magnitudes and shapes**
- **SABER is a promising new sonic boom recording device under development**
- **MiniDisc signatures offers increased frequency content for some signatures**

Slide 18

Ground signature trends are summarized in slide 19. The dominant feature of the boom signatures was the well-known N-wave shape which occurred in a number of variations. Results included cases of normal, peaked, and rounded N-waves similar to those described by Maglieri, et. al. (1972). These variations were most likely a result of atmospheric turbulence or wind shear creating distortions in the wave shape. Many deviations from an N-wave are associated with shock propagation through a turbulent atmosphere (Lipkens and Blanc-Benon, 1994). Ground measurements are particularly likely to include such distortions because of the turbulent nature of the lowest levels of the atmosphere.

Focusing conditions were reached at the ground stations for several flight conditions, resulting in U-shaped booms. The peak overpressures for some of these cases were relatively large in comparison to N-waves recorded from other flight conditions. A trend toward shorter boom event durations and lower peak overpressures was observed with decreasing gross weight.

Summary of Ground Signature Trends

- **Most common signatures were coalesced N-waves**
- **Some signatures appear to be distorted by atmospheric turbulence**
- **Focusing effects were noticed for several test conditions (U-waves)**
- **Trends in boom magnitude and duration were observed as a function of gross weight**

Slide 19

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13. ABSTRACT (Maximum 200 words)

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